

# Implications of a 125 GeV Higgs scalar for LHC SUSY and neutralino dark matter searches

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**ABSTRACT:** The ATLAS and CMS collaborations have reported an excess of events in the  $\gamma\gamma$ ,  $ZZ^* \rightarrow 4\ell$  and  $WW^*$  search channels at an invariant mass  $m \simeq 125$  GeV, which could be the first evidence for the long-awaited Higgs boson. We investigate the consequences of requiring  $m_h \simeq 125$  GeV in both the mSUGRA and NUHM2 SUSY models. In mSUGRA, large values of trilinear soft breaking parameter  $|A_0|$  are required, and universal scalar  $m_0 \gtrsim 0.8$  TeV is favored so that we expect squark and slepton masses typically in the multi-TeV range. This typically gives rise to an “effective SUSY” type of sparticle mass spectrum. In this case, we expect gluino pair production as the dominant sparticle creation reaction at LHC. For  $m_0 \lesssim 5$  TeV, the superpotential parameter  $\mu \gtrsim 2$  TeV and  $m_A \gtrsim 0.8$  TeV, greatly restricting neutralino annihilation mechanisms. These latter conclusions are softened if  $m_0 \sim 10 - 20$  TeV or if one proceeds to the NUHM2 model. The standard neutralino abundance tends to be far above WMAP-measured values unless the neutralino is higgsino-like. We remark upon possible non-standard (but perhaps more attractive) cosmological scenarios which can bring the predicted dark matter abundance into accord with the measured value, and discuss the implications for direct and indirect detection of neutralino cold dark matter.

**KEYWORDS:** Supersymmetry Phenomenology, Supersymmetric Standard Model, Large Hadron Collider.

## 1. Introduction

Recently, the ATLAS and CMS experiments have performed a combined search [1] for the Standard Model (SM) Higgs boson  $H_{SM}$  using  $1\text{--}2.3\text{ fb}^{-1}$  of integrated luminosity with the result that the region  $141\text{ GeV} < m_{H_{SM}} < 476\text{ GeV}$  is now excluded as a possibility at 95%CL. Even more recently, using the full data sample in excess of  $5\text{ fb}^{-1}$  per experiment collected in 2011, the ATLAS [2] and CMS [3] collaborations have reported excesses in the Higgs search  $\gamma\gamma$ ,  $ZZ^* \rightarrow 4\ell$  and  $WW^* \rightarrow 2\ell$  channels with reconstructed invariant mass  $m(\gamma\gamma) \sim m(4\ell) \sim 125\text{ GeV}$ . The combined statistical significance lies at the  $2.5\sigma$  level. These latest results might be construed as the first emerging direct evidence of the Higgs boson. Indeed, these new Higgs search results are consistent with the combined LEP2 [4]/Tevatron precision electroweak analyses [5] which favor the existence of a Higgs boson with mass not much beyond the LEP2 limit of  $m_{H_{SM}} > 114.4\text{ GeV}$ .

While the putative  $m_h \sim 125\text{ GeV}$  signal is consistent with SM expectations, it is rather stunning that it is also well in accord with expectations from supersymmetric models (SUSY), where the window of possible Higgs masses  $m_h$  is far smaller. In the Minimal Supersymmetric Standard Model (MSSM), the Higgs sector consists of two doublet fields  $H_u$  and  $H_d$ , which after the breaking of electroweak symmetry, result in the five physical Higgs bosons: two neutral  $CP$ -even scalars  $h$  and  $H$ , a neutral  $CP$ -odd pseudoscalar  $A$  and a pair of charged scalars  $H^\pm$  [6]. At tree level, the value of  $m_h$  is bounded by  $M_Z |\cos 2\beta|$ , where  $\tan \beta \equiv v_u/v_d$  is the ratio of Higgs field vacuum expectation values. Including radiative corrections, which depend on various sparticle masses and mixings that enter the  $h$ -boson self-energy calculation, one finds instead that  $m_h \lesssim 135\text{ GeV}$  [7]. In fact, using  $\sim 1\text{ fb}^{-1}$  of data in summer 2011, ATLAS [8] and CMS [9] had already reported some excess of  $WW^*$  events. In Ref. [10], such events had been shown to favor a rather high mass light Higgs scalar  $h$ , with mass in the  $m_h \sim 125 - 130\text{ GeV}$  range, and with large scalar masses  $m_0$  and large trilinear soft breaking terms  $A_0 \sim \pm 2m_0$  [10].

Over most of the MSSM parameter space, the lightest Higgs boson  $h$  is nearly SM-like so that SM Higgs search results can also be directly applied to  $h$  (for exceptions, see Ref. [11]). A calculation of the light (heavy) scalar Higgs boson mass at 1-loop level using the effective potential method gives

$$m_{h,H} = \frac{1}{2} \left[ (m_A^2 + M_Z^2 + \delta) \mp \xi^{1/2} \right], \quad (1.1)$$

where  $m_A$  is the mass of the  $CP$ -odd pseudoscalar  $A$  and

$$\xi = [(m_A^2 - M_Z^2) \cos 2\beta + \delta]^2 + \sin^2 2\beta (m_A^2 + M_Z^2)^2. \quad (1.2)$$

The radiative corrections can be approximated as follows

$$\delta = \frac{3g^2 m_t^4}{16\pi^2 M_W^2 \sin^2 \beta} \log \left[ \left( 1 + \frac{m_{\tilde{t}_L}^2}{m_t^2} \right) \left( 1 + \frac{m_{\tilde{t}_R}^2}{m_t^2} \right) \right]. \quad (1.3)$$

Thus, in order to accommodate a value of  $m_h \sim 125\text{ GeV}$ , we anticipate rather large values of top squark soft masses  $m_{\tilde{t}_{L,R}}$  typically at least into the few-TeV range.



For our calculation of  $m_h$ , we include the full third generation contribution to the effective potential, including all sparticle mixing effects [12]. The effective Higgs potential,  $V_{eff}$ , is evaluated with all running parameters in the  $\overline{DR}$  renormalization scheme evaluated at the scale choice  $Q_{SUSY} = \sqrt{\overline{m}_{\tilde{t}_1} \overline{m}_{\tilde{t}_2}}$ , *i.e.* the mean top squark mass scale. Of particular importance is that the  $t$ ,  $b$  and  $\tau$  Yukawa couplings are evaluated at the scale  $Q_{SUSY}$  using 2-loop MSSM RGEs and including full 1-loop MSSM radiative corrections [13]. Evaluating  $V_{eff}$  at this (optimized) scale choice then includes the most important two-loop effects [14]. This calculational procedure has been embedded in the Isajet mass spectra program Isasugra [15], which we used for the present work. We note that just a few GeV theory error is expected in our  $m_h$  calculation. Also, it should be noted that our value of  $m_h$  is typically a couple GeV below the corresponding FeynHiggs [16] calculation, mainly due to the fact that we are able to extract and use the two-loop  $\overline{DR}$  Yukawa couplings including 1-loop threshold corrections in our calculation of radiative corrections to  $m_h$ . Our calculation of  $m_h$  agrees well with results from SuSpect, SoftSUSY and Sphenocode [17].

Our goal in this paper is to calculate the implications of a 125 GeV light Higgs scalar  $h$  for supersymmetry searches at LHC, and for direct and indirect neutralino dark matter searches. In Sec. 2, we examine implications of a 125 GeV light Higgs scalar in the paradigm mSUGRA model [18]. In Sec. 3, we examine implications in the more general 2-parameter non-universal Higgs model (NUHM2). In Sec. 4, we examine implications of a 125 GeV light Higgs scalar for  $(g-2)_\mu$ ,  $BF(b \rightarrow s\gamma)$ ,  $BF(B_s \rightarrow \mu^+\mu^-)$  and for direct and indirect searches for neutralino cold dark matter (CDM). In Sec. 5, we present our conclusions.

## 2. Implications of $m_h = 125$ GeV in the mSUGRA model

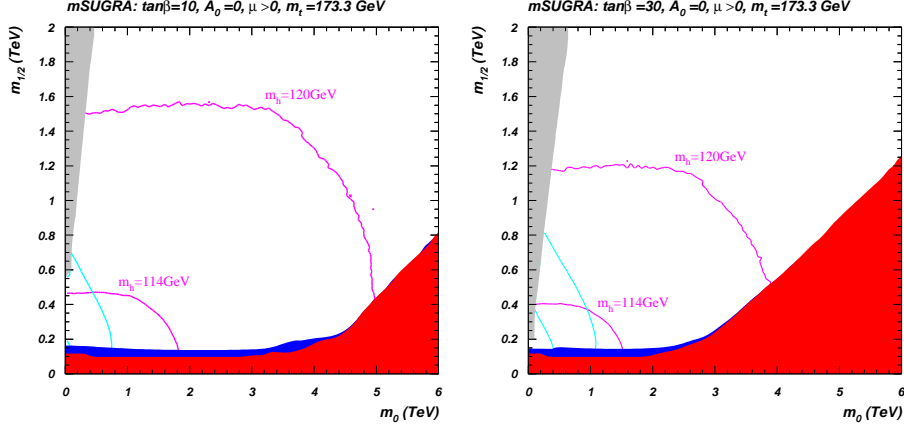
Our first goal is to examine the implications of a 125 GeV light Higgs scalar for the paradigm mSUGRA model. The well-known parameter space is given by

$$m_0, m_{1/2}, A_0, \tan\beta, \text{sign}(\mu). \quad (2.1)$$

The mass of the top quark also needs to be specified and we take it to be, throughout this paper,  $m_t = 173.3$  GeV in accord with the Tevatron results [19].

We begin by plotting contours of  $m_h$  in the  $m_0$  *vs.*  $m_{1/2}$  plane in Fig. 1a) for  $A_0 = 0$  and  $\tan\beta = 10$ , with  $\mu > 0$  (as favored by the muon magnetic moment anomaly [20]). The gray shaded region leads to a stable tau-slepton and so is excluded by cosmological constraints on long-lived charged relics. The red-shaded region is excluded by lack of appropriate radiative electroweak symmetry breaking (REWSB). The blue-shaded region is excluded by LEP2 searches [21], and indicates where  $m_{\tilde{W}_1} < 103.5$  GeV. The lower-left magenta contour denotes  $m_h = 114$  GeV, while the outer contour beginning around  $m_{1/2} \sim 1.5$  TeV denotes  $m_h = 120$  GeV. When possible, we also plot a third contour with  $m_h = 125$  GeV. However, in this case,  $m_h < 125$  GeV in the entire plane shown. A similar situation occurs in Fig. 1b), for  $A_0 = 0$  and  $\tan\beta = 30$ . Indeed, for  $A_0 = 0$ , one must move to exceedingly high values of  $m_{1/2} \sim m_0 \sim 10$  TeV to gain regions with  $m_h \sim 125$  GeV. Such mSUGRA parameter values place both gluino and squark masses in the 20 TeV range, way beyond

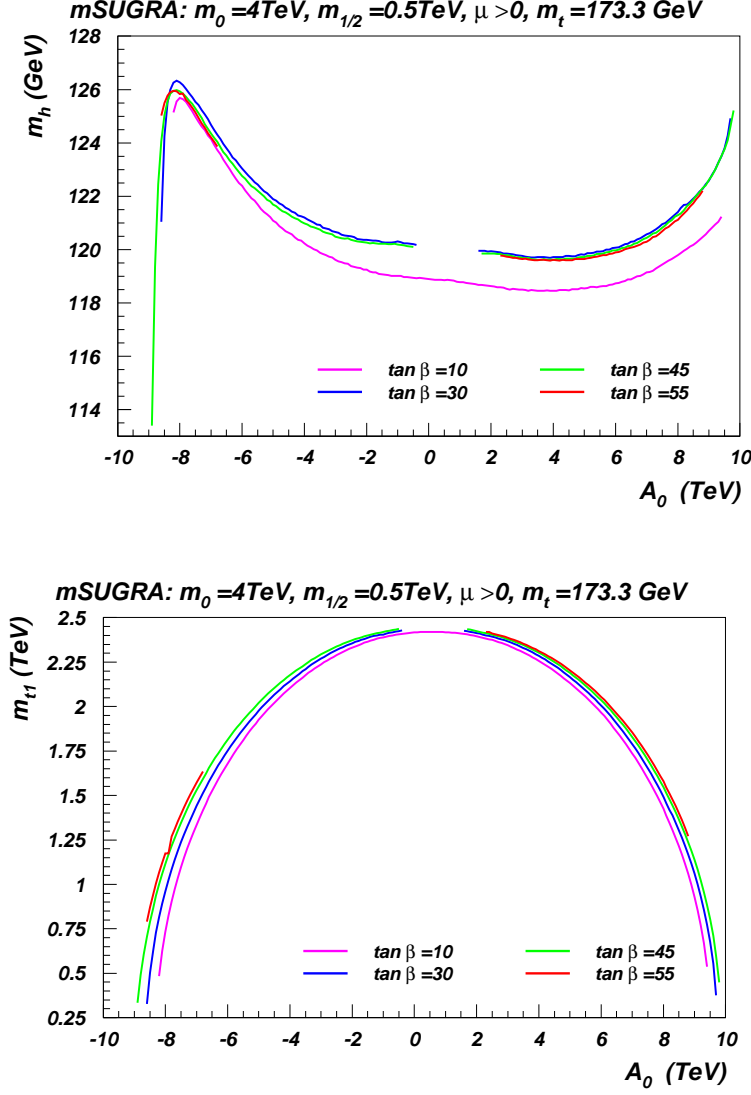
the LHC reach with  $\sqrt{s} = 7$  TeV [22] or even 14 TeV [23]. We may thus expect that the  $m_0$  vs.  $m_{1/2}$  planes of mSUGRA are excluded for  $A_0 = 0$ .



**Figure 1:** Contours of  $m_h = 114$  and  $120$  GeV (magenta) in the  $m_0$  vs.  $m_{1/2}$  plane of mSUGRA model for  $A_0 = 0$ ,  $\tan \beta = 10$  and  $30$  and  $\mu > 0$  with  $m_t = 173.3$  GeV. The region consistent with  $(g-2)_\mu$  measurement at  $3\sigma$  is between the blue contours. The gray and the red shaded regions are excluded by the stau LSP and the lack of EWSB, respectively. The blue-shaded region is excluded by the LEP2 chargino search.

The radiative corrections to  $m_h$  depend sensitively upon the top squark mixing parameter  $A_t - \mu \cot \beta$ , where  $A_t$  is the weak-scale trilinear soft breaking parameter and  $\mu$  is the superpotential higgsino mass term. For fixed  $\tan \beta$ , the mixing is largely controlled by  $A_t$ , which depends on the GUT scale value  $A_0$ . Thus, in Fig. 2a), we plot the value of  $m_h$  generated versus variation in  $A_0$  for fixed other mSUGRA parameters  $m_0 = 4$  TeV,  $m_{1/2} = 0.5$  TeV,  $\mu > 0$  and  $\tan \beta = 10, 30, 45$  and  $55$ . We see indeed that at  $A_0 = 0$ , the value of  $m_h$  is nearly minimal, while for  $A_0 \sim \pm 2m_0$ , the value of  $m_h$  is maximized, and indeed can be pushed into the 125 GeV range. The gaps in the curves around  $A_0 \sim 0$  occur due to a breakdown of radiative EWSB (beyond the hyperbolic branch/focus point (HB/FP) region [25]), while the curves terminate at very large  $|A_0|$  due to generation of tachyonic top squarks. In Fig. 2b), we show the top squark mass  $m_{\tilde{t}_1}$  versus  $A_0$  for the same parameter choices as in Fig. 2a). Here, we see the highly mixed  $\tilde{t}_1$  state is nearly at its lightest value when  $m_h$  is maximal.

Inspired by the large values of  $m_h$  for  $A_0 \sim \pm 2m_0$ , we plot the mSUGRA plane for  $A_0 = \pm 2m_0$  with  $\tan \beta = 10$  and  $30$  in Fig. 3. In Fig. 3a) with  $A_0 = -2m_0$  and  $\tan \beta = 10$ , we see that the  $m_h = 125$  GeV contour roughly independent of  $m_{1/2}$ , and lying nearly along the line at  $m_0 \simeq 2.5$  TeV. In Fig. 3b), for  $A_0 = -2m_0$  but  $\tan \beta = 30$ , the  $m_h = 125$  GeV contour is again nearly independent of  $m_{1/2}$ , this time lying nearly along the line  $m_0 \simeq 2$  TeV. In Fig. 3c), for  $A_0 = +2m_0$  and  $\tan \beta = 10$ , we see the  $m_h = 125$  GeV contour has moved out to much higher  $m_0$  values  $\sim 6 - 10$  TeV. In this case, with such large  $m_0$  values, we expect a SUSY mass spectrum of the “effective SUSY” variety, wherein scalar masses are in the multi-TeV range, and well-beyond the LHC reach [24]. However, gauginos can still be quite light, and may be accessible to LHC SUSY searches. This



**Figure 2:** Plot of a)  $m_h$  vs.  $A_0$  in the mSUGRA model for  $m_0 = 4 \text{ TeV}$ ,  $m_{1/2} = 0.5 \text{ TeV}$ ,  $\mu > 0$  and various values of  $\tan \beta$ . In frame b), we show  $m_{\tilde{t}_1}$  vs.  $A_0$  versus  $A_0$  for the same parameter choices. Curves terminate due to the lack of EWSB or because top squark becomes tachyonic.

situation persists in Fig. 3d), where we keep  $A_0 = +2m_0$ , but take  $\tan \beta = 30$ .

To make our results more general, we scan over the range

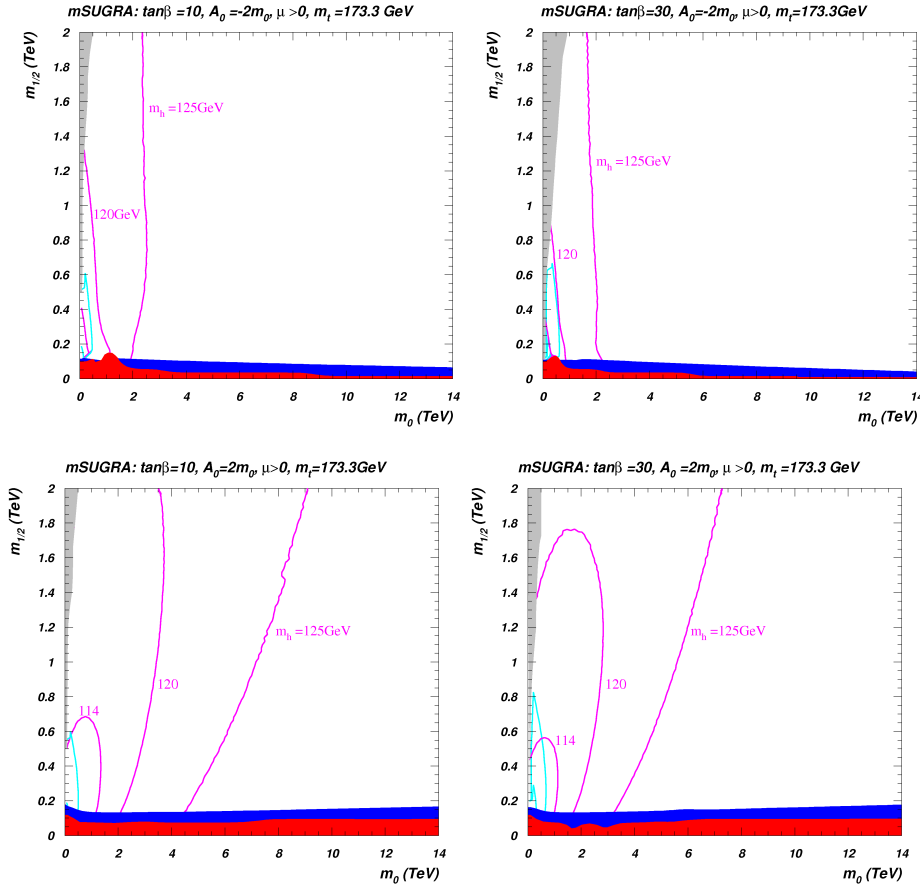
$$m_0 : 0 \rightarrow 5 \text{ TeV (blue points); } m_0 : 0 \rightarrow 20 \text{ TeV (orange points),} \quad (2.2)$$

$$m_{1/2} : 0 \rightarrow 2 \text{ TeV,} \quad (2.3)$$

$$A_0 : -5m_0 \rightarrow +5m_0, \quad (2.4)$$

$$\tan \beta : 5 \rightarrow 55. \quad (2.5)$$

We employed ISAJET 7.81 to generate 30K random points in the above parameter space,



**Figure 3:** Contours of  $m_h = 114, 120$  and  $125$  GeV in the  $m_0$  vs.  $m_{1/2}$  plane of mSUGRA model for  $A_0 = \pm 2m_0$ ,  $\tan \beta = 10$  and  $30$  and  $\mu > 0$  with  $m_t = 173.3$  GeV. The color coding is the same as in Fig. 1.

requiring only that  $m_{\tilde{W}_1} > 103.5$  GeV. The radiative electroweak symmetry breaking is maintained and the lightest supersymmetric particle (LSP) is required to be the lightest neutralino  $\tilde{Z}_1$ . We only scan over positive  $\mu$  values so that we do not stray more than  $3\sigma$  away from the measured value of the muon anomalous magnetic moment,  $(g - 2)_\mu$  [20].

A plot of the calculated  $m_h$  values from Isasugra is shown versus the various mSUGRA parameters in Fig. 4. Points with  $m_0 < 5$  TeV are denoted by blue, while points with  $5 \text{ TeV} < m_0 < 20$  TeV are denoted by orange. We see from Fig. 4a) that  $m_0 \gtrsim 0.8$  TeV is required, and much larger  $m_0$  values in the multi-TeV range are favored based on density of points. In Fig. 4b), we see that  $m_h \simeq 125$  GeV does not favor any particular  $m_{1/2}$  value, although slightly higher  $m_h$  values are allowed for very low  $m_{1/2}$  (as in Ref. [10]). In Fig. 4c), we see that  $|A_0| \lesssim 1.8m_0$  is essentially *ruled out in the mSUGRA model* in the case where  $m_0 < 5$  TeV. Also – while the entire range  $A_0 < -1.8m_0$  is allowed by our scan for  $m_0 < 5$  TeV – for positive  $A_0$ , only the narrow range  $A_0 \sim 2m_0$  seems allowed. If we allow  $m_0 > 5$  TeV, then still  $A_0 \sim 0$  is excluded, but now the allowed range drops to  $A_0/m_0 \lesssim 0.3$ . In Fig. 4d), we see that nearly the entire range of  $\tan \beta$  is allowed, except

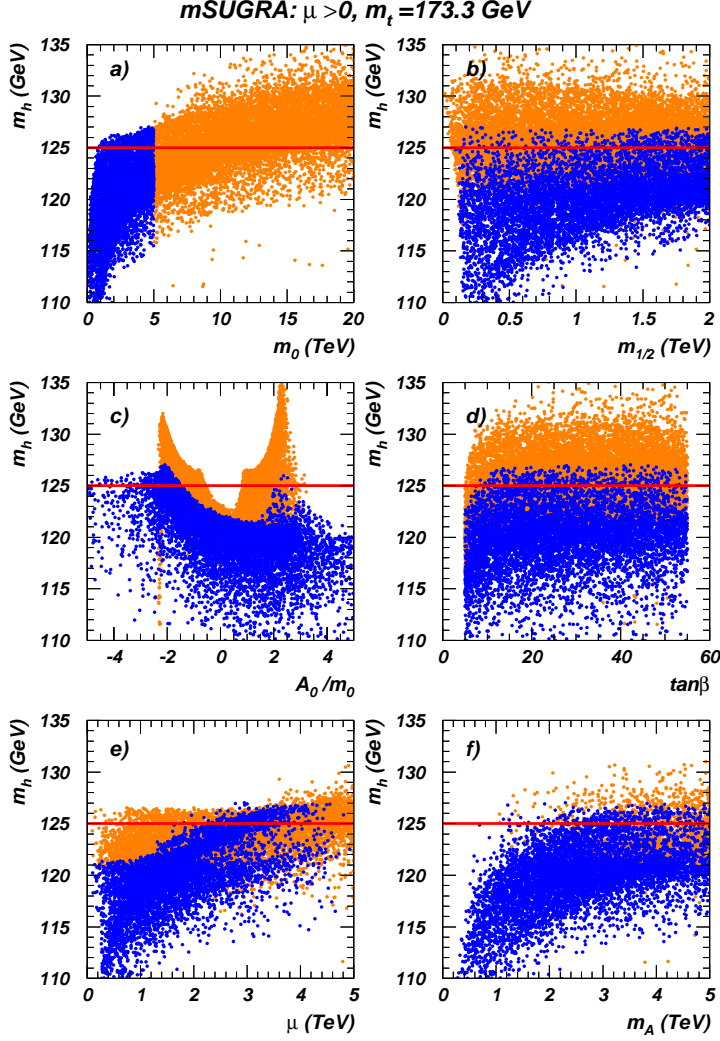
for the small region with  $\tan \beta \lesssim 6$ . A second scan (not shown here) using  $3 < \tan \beta < 60$  confirmed this result to be robust.

For the mSUGRA model, both  $|\mu|$  and  $m_A$  are derived parameters. Fig. 4e) shows that  $m_h \simeq 125$  GeV translates into the requirement  $|\mu| > 2$  TeV for  $m_0 < 5$  TeV. *This result highly restricts the possibility of light mixed bino-higgsino CDM as would occur in the lower  $m_{1/2}$  portion of the HB/FP region [25]!* However, if we allow  $m_0 \sim 5 - 20$  TeV, then low values of  $|\mu|$  become allowed. Basically, taking  $A_0/m_0$  to be large pushes the HB/FP region out to very large, multi-TeV values of  $m_0$ ; in this case, we can regain a region containing a neutralino  $\tilde{Z}_1$  of mixed bino-higgsino variety, which is characteristic of the HB/FP region, and which has a low value of the neutralino relic density,  $\Omega_{\tilde{Z}_1} h^2 \lesssim 0.1277$ . In Fig. 4f), we see that  $m_A$  is favored to be  $m_A \gtrsim 0.8$  TeV, which also restricts the possibility of  $A$ -funnel DM annihilation [26] for rather light  $\tilde{Z}_1$  states, since this possibility requires  $m_{\tilde{Z}_1} \simeq m_A/2$ .

In Fig. 5, we show points from our general scan over mSUGRA parameters (gray points for any value of  $m_h$ ) and with  $m_h = 125 \pm 1$  GeV (blue points) in the  $m_0$  vs.  $m_{1/2}$  plane. Here the most remarkable result is that the entire low  $m_0$  and low  $m_{1/2}$  region is actually excluded by requiring a large value of  $m_h \sim 125$  GeV. This bound is even more restrictive than the ATLAS and CMS direct search for SUSY limits [27, 28] which only extend up to  $m_{1/2} \sim 0.5$  TeV.

In Fig. 6 we show the distribution of the mSUGRA scan points in the  $m_0$  vs.  $A_0/m_0$  plane. Here, we see the blue points with  $m_h = 125 \pm 1$  GeV only allow for positive  $A_0 \sim 2m_0$  as long as  $m_0 \gtrsim 3 - 4$  TeV. Alternatively, large negative  $A_0$  values seem much more likely, and allow for  $m_0$  values somewhat below 1 TeV.

To gain perspective on the sort of sparticle masses we expect in mSUGRA with  $m_h = 125 \pm 1$  GeV, we plot in Fig. 7 various physical mass combinations along with the value of the superpotential  $\mu$  parameter. Gray points require  $\tilde{Z}_1$  to be the LSP,  $\tilde{W}_1$  to satisfy the lower bound of 103.5 GeV from LEP2 and has no restriction on the Higgs boson mass  $m_h$ , while blue points require  $m_h = 125 \pm 1$  GeV. Green points have in addition  $\Omega_{\tilde{Z}_1} h^2 < 0.0941$ , while red points have  $0.0941 < \Omega_{\tilde{Z}_1} h^2 < 0.1277$ , which is the  $3\sigma$  range of the WMAP-7 [45]. In Fig. 7a), we see that first/second generation squarks – typified by the  $\tilde{u}_L$  mass – are required to be  $m_{\tilde{q}} \gtrsim 2$  TeV. Meanwhile, the light top squark  $\tilde{t}_1$  usually has  $m_{\tilde{t}_1} \sim m_{\tilde{q}}/2$ , although it can range as low as a few hundred GeV. In Fig. 7b), we see a wide range of  $\tilde{t}_1$  and  $\tilde{g}$  masses are allowed, although if  $\tilde{t}_1$  is very light –  $m_{\tilde{t}_1} \lesssim 1$  TeV is favored by fine-tuning arguments – then  $m_{\tilde{g}}$  is typically lighter than 1-2 TeV as well. In Fig. 7c), we plot  $m_{\tilde{q}}$  vs.  $m_{\tilde{g}}$ . Here, we see that the lower-right region, which is the region being currently probed by SUSY searches at LHC, is already excluded if one requires  $m_h \sim 125$  GeV. In Fig. 7d), we plot the values of  $m_{\tilde{W}_1}$  vs.  $m_{\tilde{e}_L}$ , the plane which may be relevant for future  $e^+e^-$  or  $\mu^+\mu^-$  lepton colliders (LCs) operating in the TeV range. We see that sub-TeV first/second generation sleptons, as favored by the  $(g-2)_\mu$  anomaly, are essentially ruled out. However, charginos can have mass as low as  $\sim 100$  GeV, and so are still a possibility for LC searches. In Fig. 7e), we show instead the  $m_{\tilde{W}_1}$  vs.  $m_{\tilde{\tau}_1}$  plane. Here, we see that light tau sleptons with mass  $m_{\tilde{\tau}_1}$  as low as a few hundred GeV are still allowed provided that

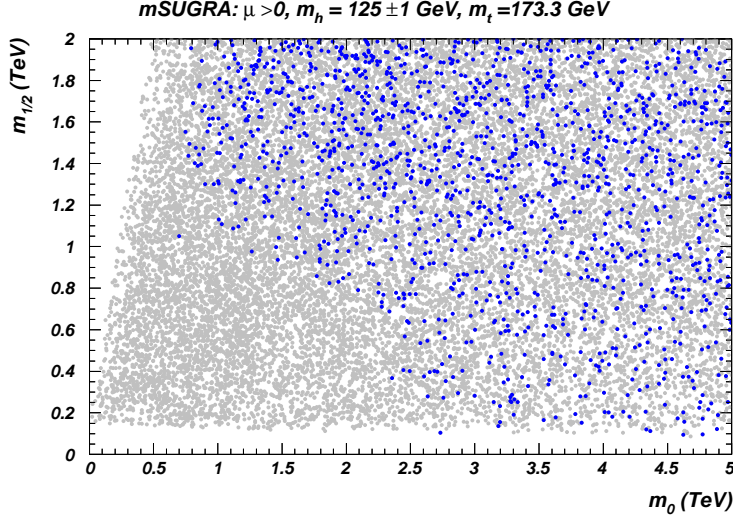


**Figure 4:** Lightest Higgs boson mass versus various parameters from the mSUGRA model for  $\mu > 0$  with  $m_t = 173.3$  GeV. Blue points denote  $m_0 < 5$  TeV, while orange points allow  $m_0$  values up to 20 TeV.

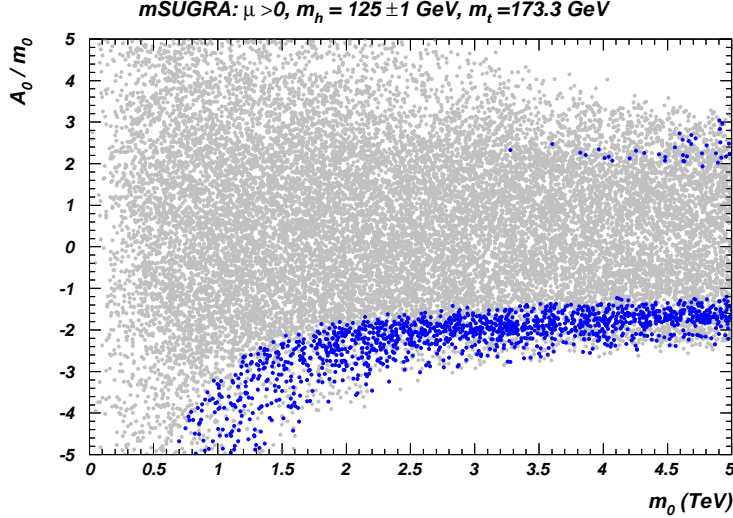
$m_{\tilde{W}_1} \gtrsim 0.6$  TeV. Finally, in Fig. 7f), we show the  $\mu$  vs.  $m_{\tilde{t}_1}$  plane. Fine-tuning arguments general favor both low  $\mu$  and low  $m_{\tilde{t}_1}$ . Here, we see that the lowest values of  $\mu$  and  $m_{\tilde{t}_1}$  would be essentially ruled out by  $m_h \sim 125$  GeV, so that mSUGRA would need to be fine-tuned.

### 3. Implications of $m_h = 125$ GeV in the NUHM2 model

Since heavy scalar masses are preferred by the rather large value of  $m_h = 125$  GeV, we next investigate the NUHM2 model [29], where large values of  $m_0$  need not be limited by



**Figure 5:** Plot of points from general scan over mSUGRA model in  $m_0$  vs.  $m_{1/2}$  plane for  $\mu > 0$  with  $m_t = 173.3$  GeV. Gray points require neutralino LSP and  $m_{\tilde{W}_1} > 103.5$  GeV, while blue points additionally require  $m_h = 125 \pm 1$  GeV.

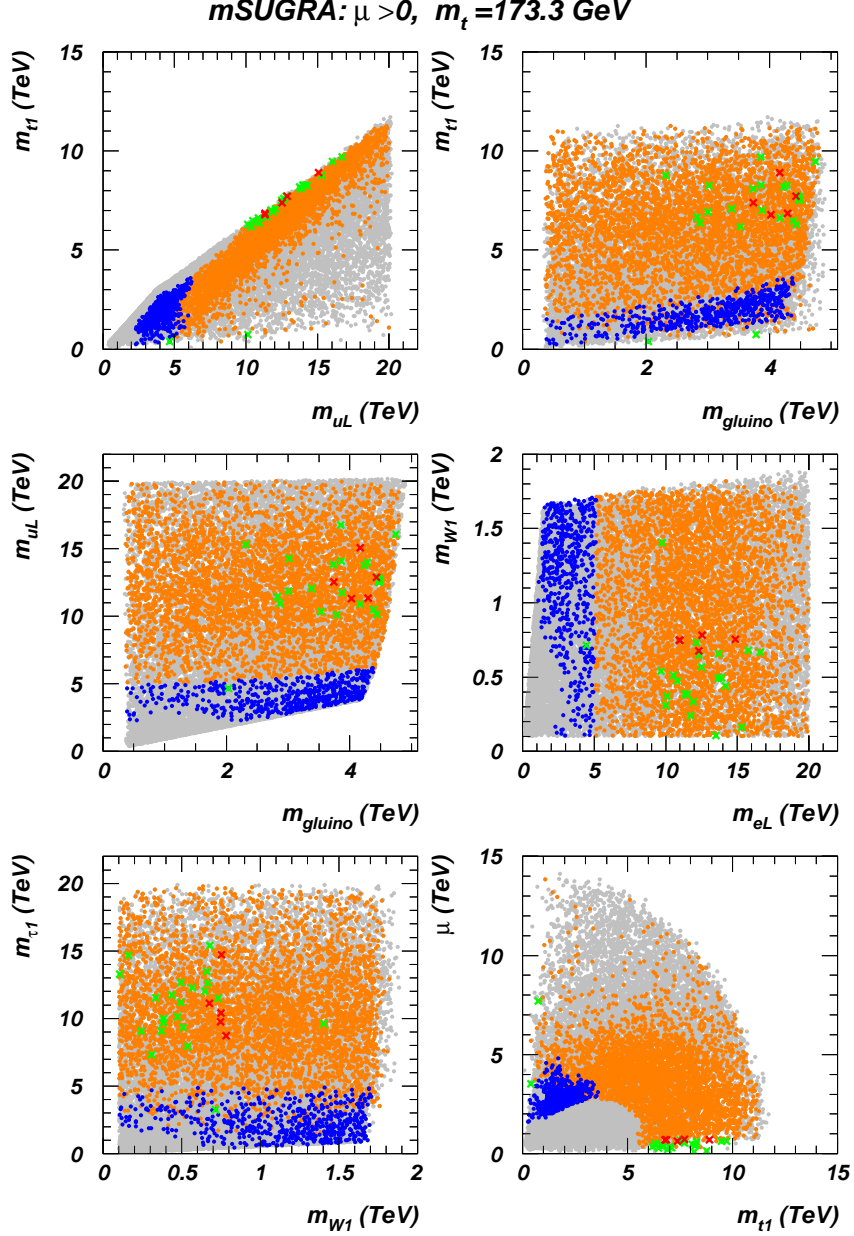


**Figure 6:** Plot of points from general scan over mSUGRA model in  $m_0$  vs.  $A_0/m_0$  plane for  $\mu > 0$  with  $m_t = 173.3$  GeV. The color coding is the same as in Fig. 5.

the onset of the HB/FP region. The NUHM2 parameter space given by

$$m_0, m_{1/2}, A_0, \tan \beta, \mu, m_A. \quad (3.1)$$

The NUHM2 model parameter space is also closer to what one may expect from SUSY GUT models where the Higgs multiplets live in different GUT representations than the matter multiplets.



**Figure 7:** Plot of points from general scan over mSUGRA model versus various physical sparticle masses and the  $\mu$  parameter for  $\mu > 0$  with  $m_t = 173.3$  GeV. Gray points require neutralino LSP and  $m_{\tilde{W}_1} > 103.5$  GeV. Blue and orange points additionally require  $m_h = 125 \pm 1$  GeV and have  $m_0 < 5$  TeV and  $5 \text{ TeV} < m_0 < 20 \text{ TeV}$ , respectively. Green and red crosses also require  $m_h = 125 \pm 1$  GeV and have the neutralino relic density  $\Omega_{\tilde{Z}_1} h^2 < 0.0941$  and  $0.0941 < \Omega_{\tilde{Z}_1} h^2 < 0.1277$ , respectively.

Similarly to the mSUGRA model described in the previous chapter, we generated 30K random points in the above parameter space, requiring only the radiative EWSB,



neutralino LSP and chargino heavier than 103.5 GeV. Our scan limits are as follows:

$$m_0 : 0 \rightarrow 5 \text{ TeV (blue points); } m_0 : 0 \rightarrow 20 \text{ TeV (orange points),} \quad (3.2)$$

$$m_{1/2} : 0 \rightarrow 2 \text{ TeV,} \quad (3.3)$$

$$A_0 : -5m_0 \rightarrow +5m_0, \quad (3.4)$$

$$\tan \beta : 5 \rightarrow 55, \quad (3.5)$$

$$\mu : 0 \rightarrow 5 \text{ TeV,} \quad (3.6)$$

$$m_A : 0 \rightarrow 5 \text{ TeV.} \quad (3.7)$$

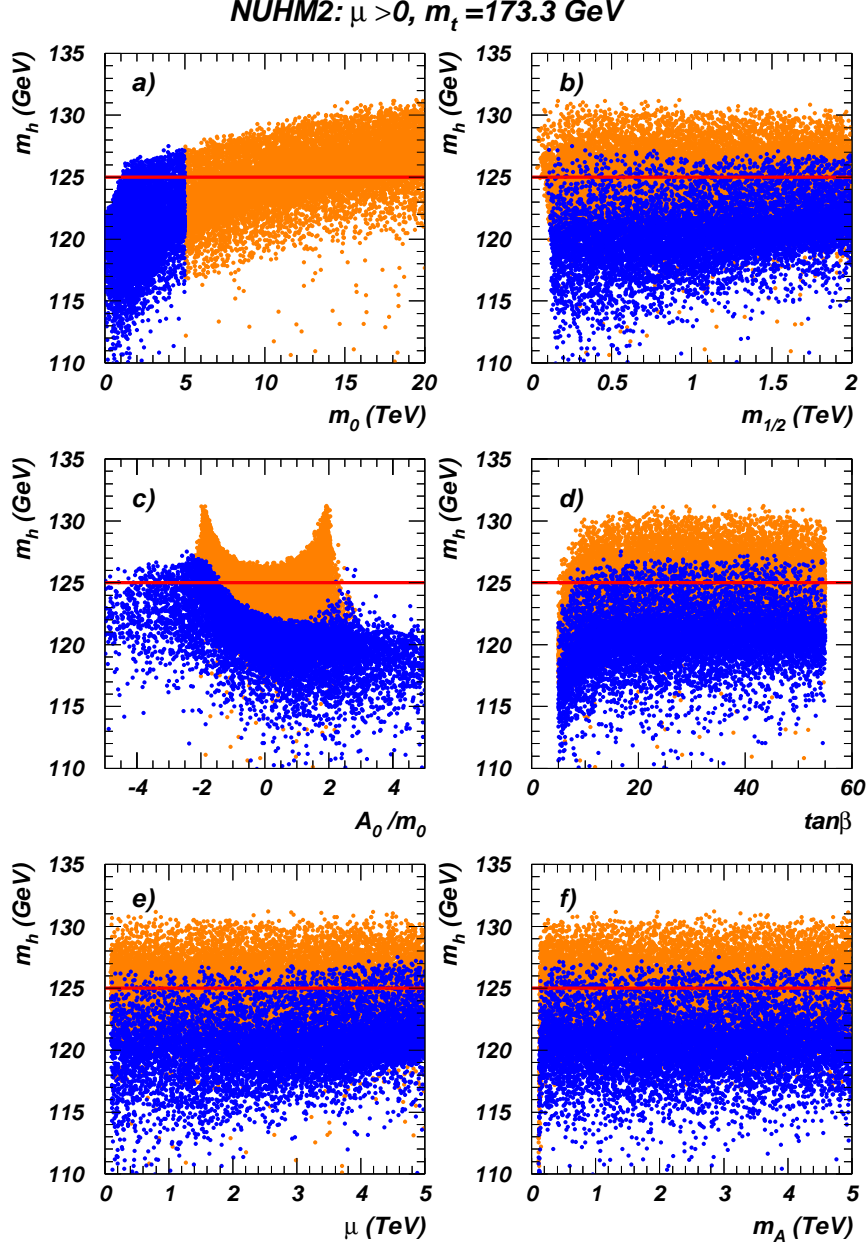
We only consider positive  $\mu$  values that are favored by the measurements of the muon anomalous magnetic moment,  $(g - 2)_\mu$  [20].

Our results in Fig. 8 show the value of  $m_h$  generated versus each model parameter. From Fig. 8a), we see that it is a rather general conclusion that in order to accommodate  $m_h \sim 125$  GeV, a rather large value of  $m_0 \gtrsim 0.8$  TeV is required. Indeed, this is consistent with early LHC SUSY searches for gluino and squark production, where  $m_{\tilde{g}} \sim m_{\tilde{q}} \gtrsim 1$  TeV is already required in gravity-mediated models with gaugino mass unification [27, 28]. In Fig. 8b), we see that no such constraint on  $m_{1/2}$  arises, and that essentially the entire range of  $m_{1/2}$  can yield a light Higgs scalar  $h$  with  $m_h \sim 125$  GeV. In Fig. 8c), we plot  $m_h$  versus  $A_0$ . If  $m_0$  is limited by 5 TeV, we see that large values of  $m_h$  consistent with 125 GeV occur when  $A_0 \sim \pm 2m_0$ , as noted previously in Ref. [10]. Also, the range  $|A_0| \lesssim 1.8m_0$  would be excluded. However, if we extend  $m_0$  up to 20 TeV, as denoted by orange points, then the range  $A_0 < 2.5m_0$  is allowed, and only  $A_0 \gtrsim 2.5m_0$  is excluded. In Fig. 8d), we plot  $m_h$  versus  $\tan \beta$  in NUHM2. Here, we see that almost the entire range of  $\tan \beta$  is allowed by requiring  $m_h \simeq 125$  GeV, except for very low values  $\tan \beta \lesssim 6$  if  $m_0 < 5$  TeV. The case where  $\tan \beta \sim 50$  includes  $t - b - \tau$  Yukawa-unified SUSY [30, 31]. In this class of models, one requires very large  $m_0 \gtrsim 10$  TeV, low  $m_{1/2}$ ,  $A_0 \sim -2m_0$  and split Higgs masses at the GUT scale, with  $m_{H_u}^2 < m_{H_d}^2$  (at  $M_{GUT}$ ) in order to accommodate REWSB. This class of models leads to an inverted scalar mass hierarchy (IMH) [32], wherein third generation scalars exist at sub-TeV values while first/second generation scalars exist at multi-TeV values. The  $t - b - \tau$  Yukawa unified models tend to predict  $m_h \gtrsim 125$  GeV, depending on how high a value of  $m_0$  is allowed<sup>1</sup>. In Fig's. 8e) and f), we plot  $m_h$  versus  $\mu$  and  $m_A$ . Here, we find – unlike in the mSUGRA case – no preference for any  $\mu$  or  $m_A$  value in scans with  $m_0$  up to either 5 or 20 TeV if  $m_h \simeq 125$  GeV.

We have seen that the existence of a light Higgs scalar  $h$  with mass  $m_h \simeq 125$  GeV leads to significant constraints on  $A_0$ ,  $\tan \beta$  and  $m_0$ . It is then worthwhile investigating correlations amongst these parameters when  $m_h \simeq 125$  GeV is required. In Fig. 9a), we show allowed NUHM2 points in the  $m_0$  vs.  $A_0/m_0$  plane. Gray colored points allow any value of  $m_h$ , while blue points require  $m_h = 125 \pm 1$  GeV. Orange points result from extending our scan in  $m_0$  up to 20 TeV. From frame a), we see that very large values of  $m_0 \gtrsim 10$  TeV are preferred by the density of model points. However, some models with  $m_h = 125 \pm 1$  GeV can be generated at much lower  $m_0$  values, especially

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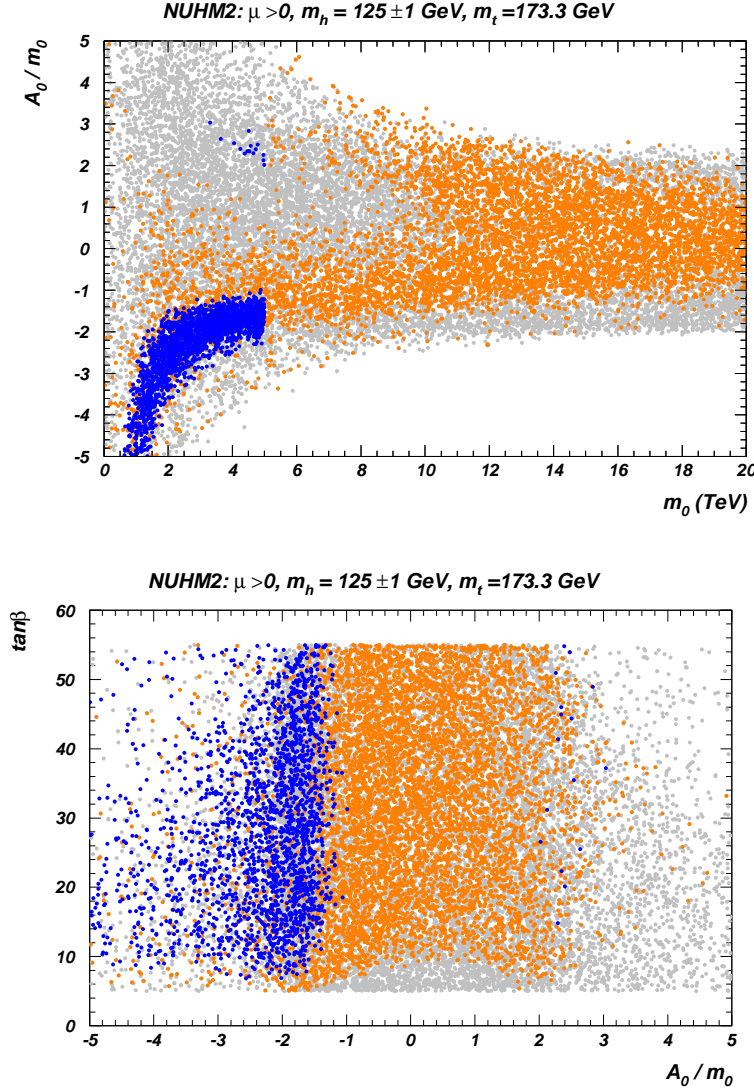
<sup>1</sup>This is already shown in Fig. 2a of the first paper of Ref [31]. For a more recent computation, see [33].



**Figure 8:** Lightest Higgs boson mass versus various SUSY parameters from a scan over NUHM2 parameter space with  $m_0$  up to 5 TeV (blue points) and  $m_0$  up to 20 TeV (orange points). We take positive  $\mu$  and  $m_t = 173.3$  GeV.

if  $A_0 < 0$ . In particular, a significant swath of parameter space with  $m_0 \lesssim 5$  TeV and  $A_0 > 0$  is evidently inconsistent with  $m_h \simeq 125$  GeV. In frame b), we plot the same points in the  $A_0/m_0$  vs.  $\tan \beta$  plane. Here, we see that the greatest density of points with  $m_h = 125 \pm 1$  GeV occurs for  $|A_0/m_0| \lesssim 3$ . However, there is an evidently new excluded

region of very low  $A_0$  values when  $\tan\beta \lesssim 6 - 8$ .



**Figure 9:** Distribution of NUHM2 points with  $m_h = 125 \pm 1$  GeV in a) the  $m_0$  vs.  $A_0/m_0$  plane and b) the  $A_0/m_0$  vs.  $\tan\beta$  plane. Gray points require neutralino LSP and  $m_{\tilde{W}_1} > 103.5$  GeV. Blue and orange points additionally require  $m_h = 125 \pm 1$  GeV and have, respectively,  $m_0 < 5$  TeV and  $5 \text{ TeV} < m_0 < 20$  TeV. We take  $m_t = 173.3$  GeV.

In Fig. 10, we plot various physical mass combinations along with the value of the superpotential  $\mu$  parameter as in Fig. 7. Again, gray points require neutralino LSP and chargino satisfying the LEP-2 bound, while blue points additionally require  $m_h = 125 \pm 1$  GeV in scans up to  $m_0 < 5$  TeV and orange points with  $m_0$  as high as 20 TeV in order to compare with Fig. 7. Green crosses have in addition  $\Omega_{\tilde{Z}_1} h^2 < 0.0941$ , while red crosses have  $0.0941 < \Omega_{\tilde{Z}_1} h^2 < 0.1277$ . In Fig. 10a), we see again that rather heavy first/second generation squarks are required, but now  $m_{\tilde{q}} \gtrsim 1.5$  TeV, somewhat lower than

in mSUGRA. The top squark  $\tilde{t}_1$  usually has  $m_{\tilde{t}_1} \sim \frac{3}{4}m_{\tilde{q}}$ , although it can also range well below this value. In Fig. 10b), we again see a wide range of  $\tilde{t}_1$  and  $\tilde{g}$  masses are allowed, with no particular correlation. In Fig. 10c), – the  $m_{\tilde{q}}$  vs.  $m_{\tilde{g}}$  mass plane, we see that the lower-right region, which was excluded in mSUGRA, now admits some solutions in the NUHM2 model. In Fig. 10d), – the  $m_{\tilde{W}_1}$  vs.  $m_{\tilde{e}_L}$  plane, we now obtain solutions with  $m_{\tilde{e}_L}$  as low as  $\sim 1$  TeV even for the case of light charginos, in contrast to the more constrained mSUGRA model case. In Fig. 10e), we find that very light, sub-TeV stau particles are allowed, which may give rise to stau co-annihilation in the early universe. And finally, in Fig. 10f), – the  $\mu$  vs.  $m_{\tilde{t}_1}$  plane – we are able to generate solutions with low  $m_{\tilde{t}_1}$  and low  $\mu$ , so that the NUHM2 model allows for much less fine-tuning than mSUGRA. We also see the green and red points with thermal neutralino relic density in accord with WMAP measurements, mainly occur at very low  $\mu$  values, indicating a  $\tilde{Z}_1$  of mixed bino-higgsino variety with a large annihilation cross section in the early universe.

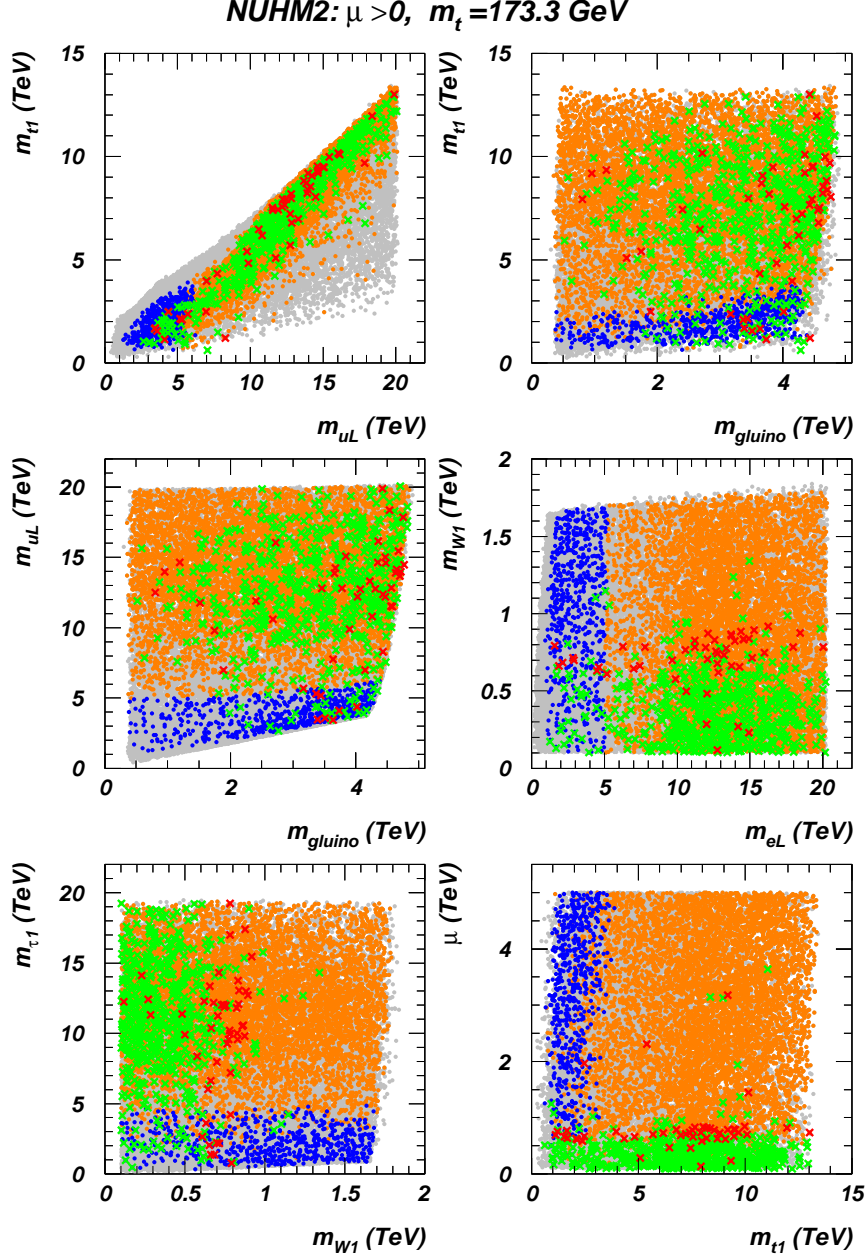
#### 4. Further implications of $m_h = 125$ GeV: rare decays, $(g-2)_\mu$ and dark matter searches

##### 4.1 $(g-2)_\mu$ and $b$ -decays

For  $(g-2)_\mu$ , we actually calculate  $a_\mu^{SUSY}$ , *i.e.* the SUSY contribution [34] to  $a_\mu \equiv \frac{(g-2)_\mu}{2}$ . In Fig. 11, we plot the value of  $a_\mu^{SUSY}$  from our scan over NUHM2 model points with the restriction that  $m_h = 125 \pm 1$  GeV. The dashed line represents the lower bar of the  $3\sigma$  range as extracted by Davier *et al.* – Ref. [35] – where it is found that the discrepancy with the SM is given by  $\Delta a_\mu = (28.7 \pm 8.0) \times 10^{-10}$ . The central value lies above the plotted range. The main point is that all allowed parameter points with  $m_h \sim 125$  GeV are inconsistent with the observed  $(g-2)_\mu$  anomaly! This is because a large value of  $m_h \sim 125$  GeV favors large  $m_0$  and  $A_0$ , which leads to a decoupling of the SUSY contribution to  $(g-2)_\mu$ . While  $m_h \sim 125$  GeV tends to favor high  $m_0$ , the discrepancy with the measured value of  $(g-2)_\mu$  only increases as  $m_0$  increases.

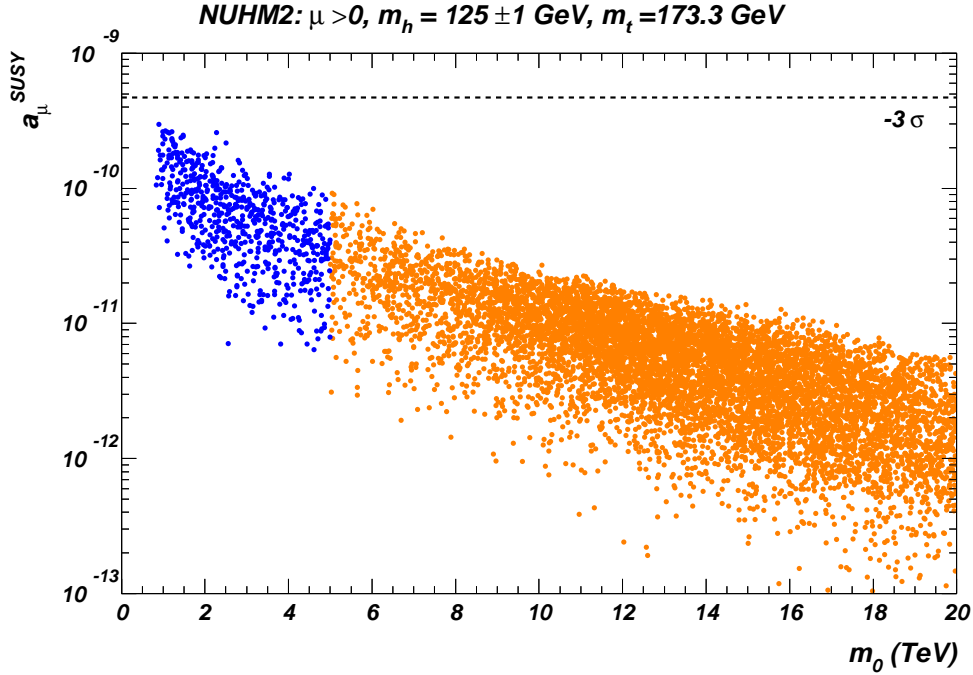
In Fig. 12, we plot the value of  $BF(b \rightarrow s\gamma)$  [37] from all SUSY points in NUHM2 parameter space with  $m_h = 125 \pm 1$  GeV. For  $BF(b \rightarrow s\gamma)$ , the solid line gives the measured central value and the dashed lines represent the  $3\sigma$  range from Ref. [36], where  $(3.55 \pm 0.26) \times 10^{-4}$  is reported. We see that most NUHM2 points tend to cluster around  $BF(b \rightarrow s\gamma) \sim 3.1 \times 10^{-4}$ , which is the expected SM value. In this case, the large value of  $m_0$  preferred by  $m_h \sim 125$  GeV tends to give a decoupling effect, although certainly values of  $BF(b \rightarrow s\gamma)$  as high as the central value are common.

In Fig. 13, we show the values of branching fraction  $BF(B_s \rightarrow \mu^+\mu^-)$  [38] from NUHM2 models with  $m_h = 125 \pm 1$  GeV. The dashed line represents the 95% CL upper limit from the CMS experiment [39]:  $BF(B_s \rightarrow \mu^+\mu^-) < 1.9 \times 10^{-8}$ . A similar limit from the LHCb experiment [40] gives  $BF(B_s \rightarrow \mu^+\mu^-) < 1.6 \times 10^{-8}$ . The CDF experiment claims evidence for a signal, but still derives a 95% CL upper limit  $BF(B_s \rightarrow \mu^+\mu^-) < 3.9 \times 10^{-8}$ . For illustration, we show the CMS result in the plot. The bulk of points cluster around the SM expectation of  $3.2 \times 10^{-9}$ , which is also the SUSY decoupling limit.



**Figure 10:** Plot of points from general scan over NUHM2 model versus various physical sparticle masses and the  $\mu$  parameter for  $\mu > 0$  with  $m_t = 173.3$  GeV. The color coding is the same as in Fig. 7.

In Fig. 14 we plot the calculated ratio of branching fractions  $R \equiv BF(B_u \rightarrow \tau^+ \nu_\tau)_{\text{MSSM}} / BF(B_u \rightarrow \tau^+ \nu_\tau)_{\text{SM}}$  vs.  $m_0$  from NUHM2 models with  $124 \text{ GeV} < m_h < 126 \text{ GeV}$ . The SM amplitude for this decay occurs via  $W$ -boson exchange, whilst the MSSM contribution occurs via  $H^+$  exchange[42]. The interference is dominantly negative except at very high  $\tan \beta$  and low

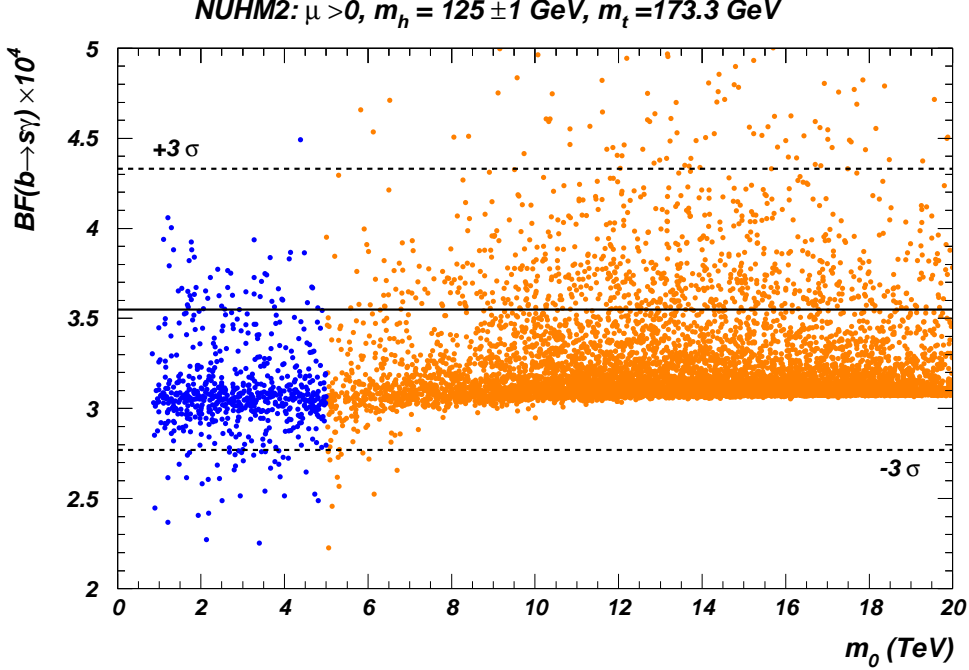


**Figure 11:** Distribution of the SUSY contribution to the muon magnetic moment  $a_\mu^{SUSY}$  vs.  $m_0$  from scan over NUHM2 parameters restricted by  $m_h = 125 \pm 1$  GeV. Blue points denote  $m_0 < 5$  TeV, while orange points allow  $m_0$  values up to 20 TeV. The dashed line represents the lower bar of the experimental  $3\sigma$  range[20].

$m_{H^+}$ . We also show the experimentally-measured central value[43] and the  $\pm 2\sigma$  deviation. The bulk of points lie close to the SM-predicted value, while many others exhibit negative interference with  $R < 1$ , and some are even excluded. A few points give a positive enhancement in agreement with the measured trend.

#### 4.2 Implications for neutralino dark matter

Next, we examine implications of  $m_h \simeq 125$  GeV for the neutralino dark matter. We calculate the thermal neutralino abundance using IsaReD [44], which includes all relevant neutralino annihilation and co-annihilation reactions along with relativistic thermal averaging of neutralino (co)-annihilation cross sections times relative velocity. The value of  $\Omega_{\tilde{Z}_1} h^2$  is plotted versus  $m_{\tilde{Z}_1}$  from NUHM2 model points with  $m_h = 125 \pm 1$  GeV in Fig. 15. The WMAP-7 reported the value [45] of  $\Omega_{CDM} h^2 = 0.1109 \pm 0.0056$  (68% CL) and we plot the  $3\text{-}\sigma$  range as the green band. We see that the bulk of SUSY points with  $m_h \simeq 125$  GeV have a large *overabundance* of thermal neutralino dark matter, with  $\Omega_{\tilde{Z}_1} h^2 \sim 1 - 10^4$  being typical, so that under a standard cosmology, these points would be excluded. There also exists a lower band crossing  $\Omega_{\tilde{Z}_1} h^2 \sim 0.1$  at  $m_{\tilde{Z}_1} \sim 0.8$  TeV: this is the case where  $\tilde{Z}_1$  is a mixed bino-higgsino state: it would seem to imply that under a standard cosmology, we would expect a 0.8 TeV higgsino/bino-like neutralino as the DM candidate.

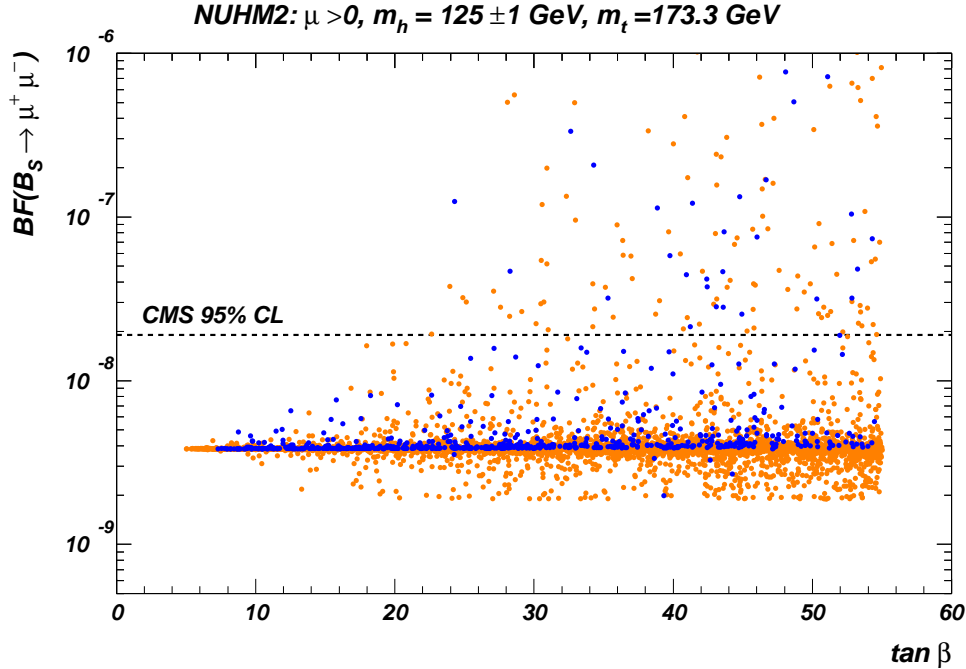


**Figure 12:** Value of  $BF(b \rightarrow s\gamma)$  vs.  $m_0$  from scan over NUHM2 parameters restricted by  $m_h = 125 \pm 1$  GeV. Blue points denote  $m_0 < 5$  TeV, while orange points allow  $m_0$  values up to 20 TeV. The solid line gives the measured central value and the dashed lines represent the  $3\sigma$  range [36].

It has been shown in several papers that the presence of a multi-TeV modulus field which decays late and dilutes all relics via entropy injection can bring a large thermal overabundance of neutralino CDM into accord with measurement [46]. Also, the presence of a light axino  $\tilde{a}$  (arising from the PQ [47] solution to the strong  $CP$  problem) can eliminate a neutralino overabundance, since each massive neutralino may decay to a light axino: in this case the relic abundance is reduced by a factor [48]  $\frac{m_{\tilde{a}}}{m_{\tilde{Z}_1}} \Omega_{\tilde{Z}_1} h^2$ . Then, the remaining dark matter abundance can be built up from axions produced via coherent oscillations [49]. Furthermore, the case of an *underabundance* of light higgsino-like neutralinos can be boosted by thermal axino production and decay in a scenario with mixed axion/neutralino CDM [50, 51].

In Fig. 16, we plot the spin-independent neutralino-proton direct detection (DD) cross section versus  $m_{\tilde{Z}_1}$  from our scan over NUHM2 models with  $m_h = 125 \pm 1$  GeV. We also plot the latest limit from the Xenon-100 collaboration [52]. We see that by far the bulk of points lie below, and most very much below, the current Xenon-100 bound. Green crosses have in addition  $\Omega_{\tilde{Z}_1} h^2 < 0.0941$ , while red crosses have  $0.0941 < \Omega_{\tilde{Z}_1} h^2 < 0.1277$ . The green points tend to come from nearly pure higgsino-like neutralinos with a standard underabundance. In models of mixed axion- $\tilde{Z}_1$  CDM, neutralinos with a standard underabundance tend to get an increased abundance from axino and saxion production and decay, so that neutralinos tend to dominate over axions as the main component of CDM. We see that these points





**Figure 13:** Value of  $BF(B_s \rightarrow \mu^+ \mu^-)$  vs.  $m_0$  from scan over NUHM2 parameters restricted by  $m_h = 125 \pm 1$  GeV. Blue points denote  $m_0 < 5$  TeV, while orange points allow  $m_0$  values up to 20 TeV. The dashed line represent the 95% CL upper limit from the CMS [39].

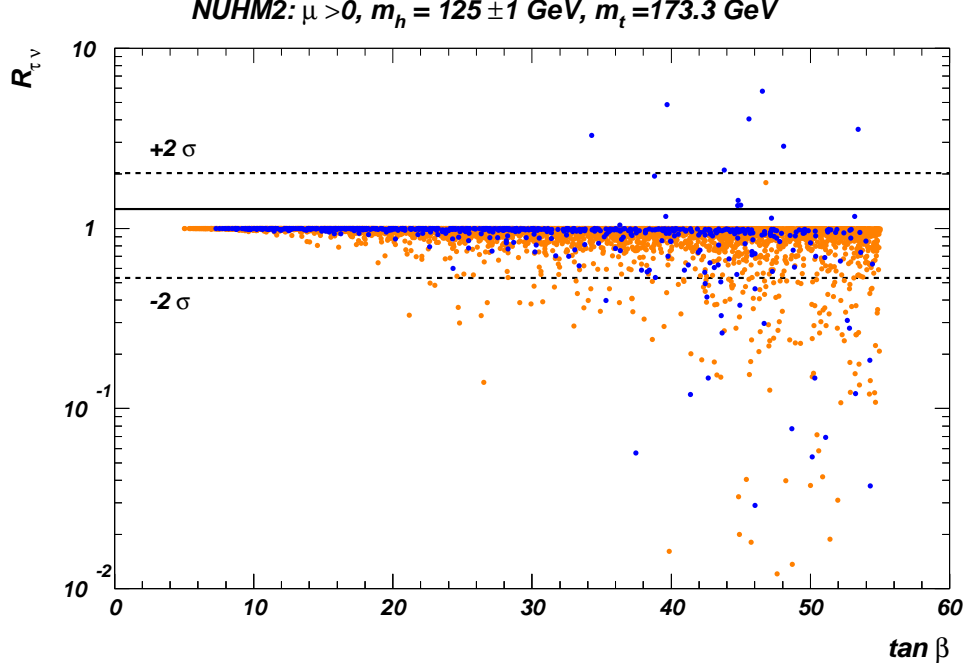
tend to cluster around  $\sigma(\tilde{Z}_1 p) \sim 10^{-9} - 10^{-8}$  pb as is typical in models with a well-tempered neutralino [53], and would likely be accessible to future runs of DD experiments.

In Fig. 17, we plot the thermally-averaged neutralino annihilation cross section times relative velocity in the limit as  $v \rightarrow 0$ :  $\langle \sigma v \rangle|_{v \rightarrow 0}$ . This quantity enters estimates of the rate for indirect dark matter detection (IDD) via observation of gamma rays and anti-matter from neutralino annihilation in the galactic halo. Recently, limits have been imposed on this cross section due to the Fermi-LAT collaboration examination of dwarf spheroidal galaxies [54]. We see that models with a standard underabundance – the line of green dots with typically higgsino-like neutralinos – may ultimately give an observable signal, while models with a standard overabundance tend to have very low annihilation rates, leading to low IDD rates. The green underabundance points – as mixed bino-higgsino states – tend to annihilate dominantly into  $WW$  and  $ZZ$  final states.

## 5. Conclusions

Evidence has been presented by ATLAS and CMS at the  $\sim 2.5\sigma$  level for the existence of a light Higgs scalar with mass  $m_h \simeq 125$  GeV. If this evidence is bolstered by an increased data sample in 2012, then the discovery will have strong implications for supersymmetric models. We have examined both the mSUGRA model and the NUHM2 model under the restriction that  $m_h = 125 \pm 1$  GeV.





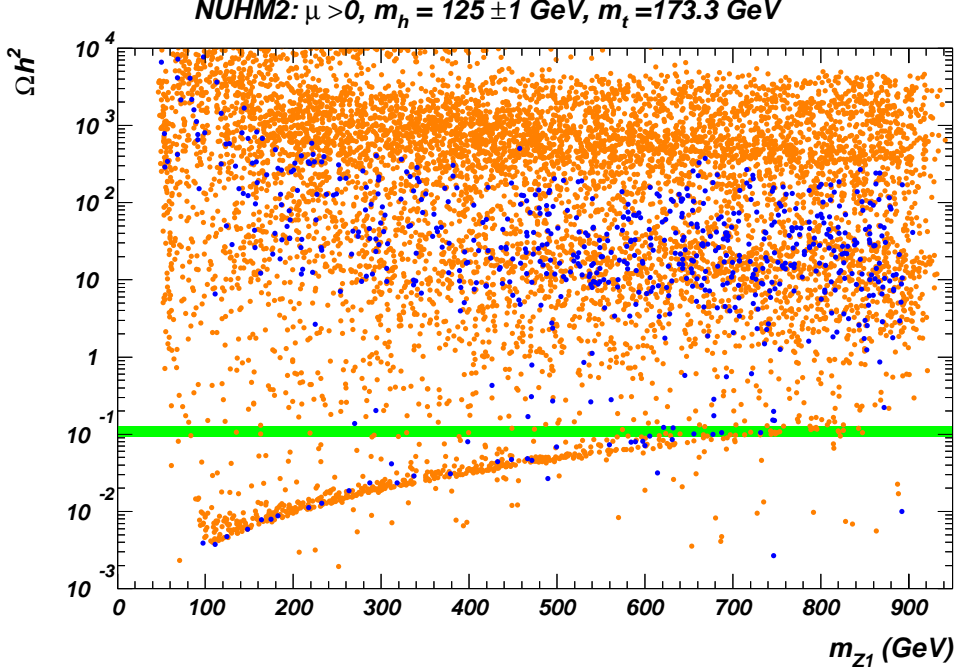
**Figure 14:** Value of  $R \equiv BF(B_u \rightarrow \tau^+ \nu_\tau)_{MSSM} / BF(B_u \rightarrow \tau^+ \nu_\tau)_{SM}$  vs.  $m_0$  from scan over NUHM2 parameters restricted by  $m_h = 125 \pm 1$  GeV. Blue points denote  $m_0 < 5$  TeV, while orange points allow  $m_0$  values up to 20 TeV. The solid line denotes the central experimental value, while dashed lines represent the  $\pm 2\sigma$  error bars[43].

In the case of the mSUGRA (CMSSM) model, we conclude the following.

- The common GUT scale scalar mass  $m_0 \gtrsim 0.8$  TeV. This tends to imply that squark and slepton masses are  $> 2$  TeV with  $m_{\tilde{q}} > m_{\tilde{g}}$ . In fact, the entire low  $m_0$ , low  $m_{1/2}$  region of the mSUGRA plane is ruled out independent of  $A_0$  or  $\tan \beta$  values.
- The soft breaking trilinear parameter  $|A_0| \lesssim 1.8m_0$  is excluded for  $m_0 < 5$  TeV, or  $|A_0| \lesssim 0.3m_0$  is excluded if  $m_0$  ranges up to 20 TeV.
- The superpotential Higgs mass term  $\mu \gtrsim 2$  TeV for  $m_0 \lesssim 5$  TeV. This strongly restricts mixed higgsino-bino states as a source of thermal neutralino CDM, as would be found in the HB/FP region. This constraint is relaxed if  $m_0$  lies in the 5 – 20 TeV range.
- $m_A \gtrsim 0.8$  TeV, which means  $m_{\tilde{Z}_1} \gtrsim 0.4$  TeV if neutralinos annihilate through the  $A$ -resonance.

In the case of NUHM2 model, we find:

- $m_0 \gtrsim 0.8$  TeV as in mSUGRA,
- for  $m_0 < 5$  TeV, then  $A_0 \lesssim -1.8m_0$  or  $A_0 \sim +2m_0$ ,

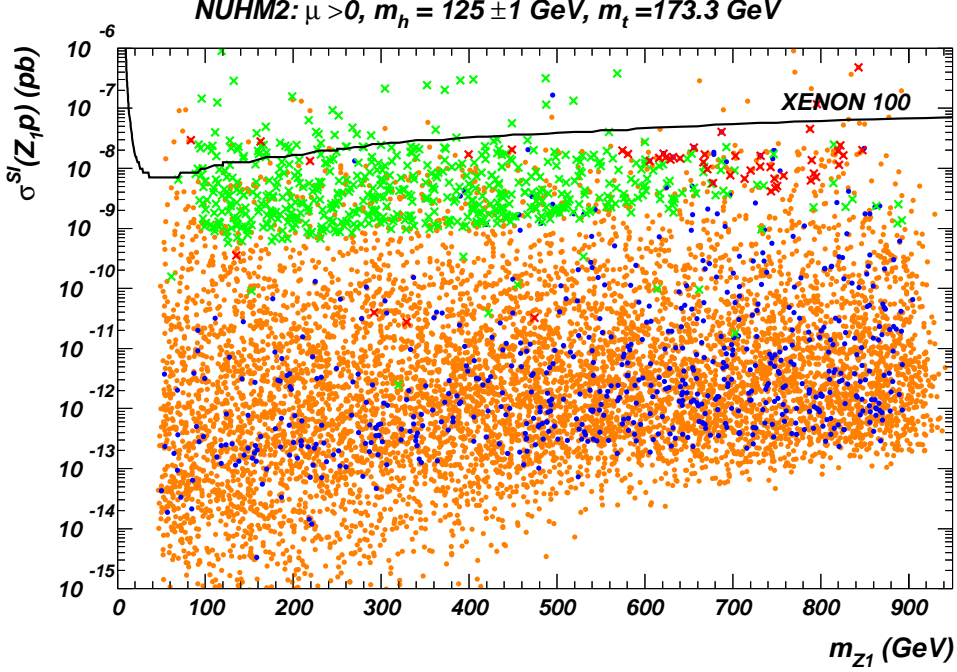


**Figure 15:** Neutralino relic density  $\Omega_{\tilde{Z}_1} h^2$  versus the neutralino mass  $m_{\tilde{Z}_1}$  from scan over NUHM2 parameters with  $m_h = 125 \pm 1$  GeV. Blue points denote  $m_0 < 5$  TeV while orange points allow  $m_0$  values up to 20 TeV. The shaded green horizontal band represents the WMAP 3- $\sigma$  range [45].

- for  $m_0 \sim 5 - 20$  TeV, then just  $A_0 \lesssim 2.5m_0$  is required,
- unlike mSUGRA, the entire ranges of  $\mu$  and  $m_A$  are still allowed,
- thermally produced neutralinos match the WMAP-measured relic abundance for a mixed higgsino state at  $m_{\tilde{Z}_1} \sim 0.7$  TeV.

In addition, for NUHM2 and mSUGRA models,

- A value of  $m_h \simeq 125$  GeV is inconsistent with the  $(g - 2)_\mu$  anomaly. If the anomaly turns out to be real, it may imply alternative models such as “normal scalar mass hierarchy” [55] where first/second generation GUT scalar masses  $m_0(1,2)$  are much lighter than third generation scalars  $m_0(3)$ .
- A value of  $m_h \simeq 125$  GeV is completely consistent with the measured values of  $BF(b \rightarrow s\gamma)$ ,  $BF(B_s \rightarrow \mu^+\mu^-)$  and  $BF(B_u \rightarrow \tau^+\nu_\tau)$ .
- Neutralino CDM is typically overproduced in the standard MSSM cosmology, unless the neutralino is higgsino-like, in which case its mass is around 0.8 TeV. In non-standard cosmologies, such as those including late decaying moduli fields or mixed axion/LSP CDM, the CDM abundance can be easily brought into accord with measured values.



**Figure 16:** Neutralino spin-independent direct detection cross section  $\sigma(\tilde{Z}_1 p)$  vs.  $m_{\tilde{Z}_1}$  from a scan over NUHM2 model points restricted by  $m_h = 125 \pm 1$  GeV. Blue points denote  $m_0 < 5$  TeV, while orange points allow  $m_0$  values up to 20 TeV. Green and red crosses have the neutralino relic density  $\Omega_{\tilde{Z}_1} h^2 < 0.0941$  and  $0.0941 < \Omega_{\tilde{Z}_1} h^2 < 0.1277$ , respectively. The solid black curve represents the limit from the XENON 100 experiment [52].

- Direct and indirect WIMP detection rates tend to be very low for models with a standard overabundance of CDM. In the case of higgsino-like WIMPs with a standard underabundance, direct and indirect detection prospects are rather bright.

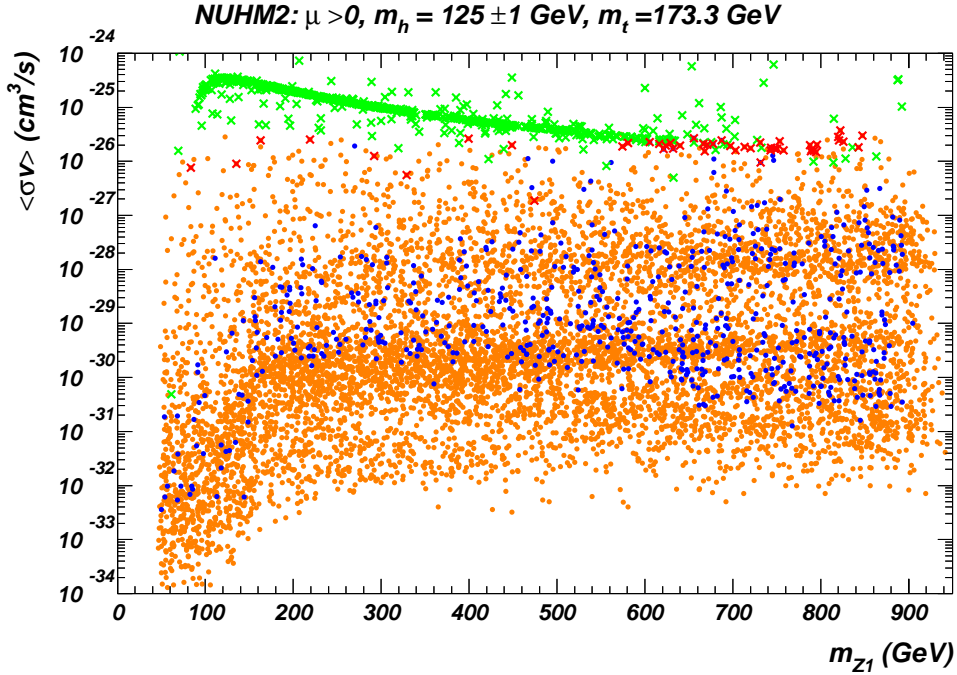
**Note Added:** After this work was finished, several papers appeared that also investigated implications of the recent LHC Higgs search results on mSUGRA and NUHM models [56]. Their results tend to agree with ours although small differences do arise due to differences in the considered ranges of model parameters.

## Acknowledgments

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**Figure 17:** Thermally averaged neutralino annihilation cross section times relative velocity  $\langle\sigma v\rangle$  vs.  $m_{\tilde{Z}_1}$  from scan over NUHM2 points restricted by  $m_h = 125 \pm 1 \text{ GeV}$ . The color coding is the same as in Fig. 16.

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